

# In Search of Lonely Top Quarks at the Tevatron \*

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Single top-quark production, via weak-interaction processes, is an important test of the standard model, potentially sensitive to new physics. However, this measurement is much more challenging at the Tevatron than originally expected. We reexamine this process and suggest new methods, using shape variables, that can supplement the methods that have been discussed previously.

The electroweak production of single top quarks is an important standard model process which the Tevatron is guaranteed to be able to study. This reaction, which has been investigated previously [1, 2], is interesting both because it provides a direct measurement of the  $V_{tb}$  CKM element and because it is sensitive to deviations of top quark physics from standard model predictions[3]. Limits on single top production from Run I at the Tevatron have been published [4, 5], and the first Run II limits have appeared [6, 7]. This discussion will provide a brief overview on our recent work on this subject [8]. The executive summary is that a) this process will be more difficult to study experimentally than previously thought, b) we have developed new analysis methods, which will improve the significance of the measurement, and c) even with our new analysis methods the unambiguous detection of this process remains a considerable challenge. In particular, we suggest making use of more of the information encoded in the shape of the signal, in a way that will be less sensitive to systematic errors than a simple counting experiment. On the other hand, we also show that the size of and the uncertainties in the  $W$ -plus-jets background cause serious problems that at present make the measurement difficult at best.

At Fermilab energies, the “ $tb$ ” production of a top quark and bottom antiquark by an  $s$ -channel  $W$  boson, as can occur through the diagram in

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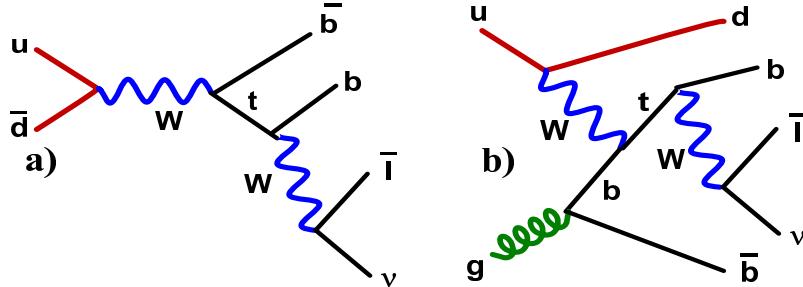


Fig. 1. Single top quark production via a) an  $s$ -channel  $W$ , b) a  $t$ -channel  $W$ .

Fig. 1a), has a lower cross-section than “ $tbq$ ” production via a  $t$ -channel  $W$  boson of a  $t$ ,  $\bar{b}$ , and an extra quark jet near the beam axis, as occurs through diagrams such as that in Fig. 1b).

From Fig. 1b) one can see that a  $tbq$  event has a final partonic state consisting of at least the following: a charged lepton, a neutrino,  $b$  and  $\bar{b}$  quarks, and a light quark. Thus, in selecting  $t$ -channel signal events, one asks for (a) one  $b$ -tagged jet, (b) significant missing energy (from the neutrino), (c) one and only one isolated  $e^\pm$  or  $\mu^\pm$ , (d) at least one non- $b$ -tagged jet. Typically, the highest- $p_T$  non- $b$ -tagged jet in a  $t$ -channel event is that from the light quark. Also, in typical events a  $t$  quark can be reconstructed from the tagged jet and a  $W$ , itself reconstructed from the charged lepton and the missing energy. The  $tb$  process has a  $b$  quark jet and a  $\bar{b}$  jet, along with a lepton and a neutrino. In a significant number of events, one of the two  $b$ -jets will not be tagged, so that the same criteria used for  $tbq$  will have moderately high efficiency for this process as well.

The main backgrounds to single top production, which all can imitate the signature just described, are [1] (1) “ $t\bar{t}$ ”, top quark pair production, primarily from events where only one of the top quarks decays leptonically; (2) “QCD” events with fake electrons or muons, or with real muons from heavy flavor decays; and, most problematic, (3) “ $Wj^n$ ” events with a leptonically-decaying  $W$  plus some number  $n \geq 2$  of quark or gluon jets. Processes of all three types occur at rates well above the signal rate and so we must provide specialized cuts and other methods to reduce their contribution to the final event sample. For example, the  $t\bar{t}$  background events tend to exhibit considerably more transverse energy than true single top events, to have more jets, and to be more spherical. Experience with the QCD background suggests that it is generally reduced to a level comparable with the signal [7] by fairly standard cuts and we will not focus on it here, except to note that our event shape methods will tend to also substantially reduce the QCD component of

the event sample. The  $W$ -plus-jets background is much more complicated. The  $Wj^n$  events potentially entering the sample consist of a real  $W$  boson decaying leptonically, and at least two other quarks or gluons in the final state. While the  $Wj^n$  events do tend to have smaller energetics than single top, and, of course, have no reconstructible  $t$  quark; the number of events is so large, and the energy resolution at Fermilab is sufficiently broad, that the  $Wj^n$  events form a large and problematic background to single-top production. Reducing the systematic error on the prediction and/or measurement of this process is essential for success.

To model both signal and background, we have used MadEvent [9] to generate events, Pythia [10] to then simulate showering and hadronization, and PGS [11] to act as a fast detector simulation. (See [8] for the details of the calculations.) Jets containing a  $b$  quark (either perturbatively or produced during showering) are taken to be tagged with an efficiency of the form  $0.5 \tanh(p_T/36 \text{ GeV})$ , where  $p_T$  is the transverse momentum of the jet. Jets containing a  $c$  quark (either perturbatively or produced during showering) are taken to be tagged with a rate of the form  $0.15 \tanh(p_T/42 \text{ GeV})$ ; while jets containing no heavy flavor are taken to be mistagged with a rate of the form  $0.01 \tanh(p_T/80 \text{ GeV})$ .

We have chosen for this study to cut also on the quantity

$$H_T = \sum_{\text{jets}} (p_T)_i + (p_T)_\ell + \cancel{E}_T ,$$

which, compared to the signal, is smaller for  $Wj^n$  and larger for  $t\bar{t}$ . In this expression the sum is over all jets with  $p_T > 20 \text{ GeV}$  and  $|\eta| < 3.5$ ,  $(p_T)_i$  is the magnitude of the transverse momentum of the  $i^{\text{th}}$  jet,  $(p_T)_\ell$  that of the lepton, and  $\cancel{E}_T$  is the missing transverse energy in the event. Since the signal involves a  $t$ -quark, we also impose a requirement that the invariant mass of the lepton, neutrino, and the leading tagged jet be within a window around the top quark mass.

We find that such cuts cannot decrease the backgrounds to the point that they are comparable to the signal. Two choices of “intermediate” and “hard” cuts are indicated in Table 1. The resulting numbers of expected events for an integrated luminosity of  $3 \text{ fb}^{-1}$ , summing over  $e^\pm$  and  $\mu^\pm$  (and thus including both  $t$  and  $\bar{t}$ ), can be seen in Table 2. Consistent with [1], we find that while all of the cuts contribute to the background reduction, the  $Wj^n$  channel is reduced primarily by a combination of the stiffer  $p_T$  cuts and the “ $m_t$ ” cut, while the  $t\bar{t}$  background is affected primarily by the upper  $H_T$  cut. While the intermediate cuts reveal a signal to background ratio of 1:7.4, this improves to 1:4.9 using the hard cuts. (The basic cuts used as a starting point in [8] yield a signal to background ratio of approximately 1:21.) This result is, at best, disappointing and more pessimistic than [1].

Item	$p_T$	$ \eta $	$p_T$	$ \eta $
$\ell^\pm$	$\geq 15$ GeV	$\leq 2$	$\geq 15$ GeV	$\leq 2$
MET ( $\nu$ )	$\geq 15$ GeV	-	$\geq 15$ GeV	-
jet ( <i>b</i> -tag)	$\geq 20$ GeV	$\leq 2$	$\geq 60$ GeV	$\leq 2$
jet (no <i>b</i> -tag)	$\geq 20$ GeV	$\leq 3.5$	$\geq 30$ GeV	$\leq 3.5$
	Min	Max	Min	Max
$H_T$	$\geq 180$ GeV	$\leq 250$ GeV	$\geq 180$ GeV	$\leq 250$ GeV
“ $m_t$ ”	$\geq 160$ GeV	$\leq 190$ GeV	$\geq 160$ GeV	$\leq 190$ GeV

Table 1. Representative “intermediate” cuts (columns 2 and 3) and “hard” cuts (columns 4 and 5).

Channel	“Intermediate” Cuts	“Hard” Cuts
$tbq$	67	30
$tb$	27	13
$t\bar{t}$	140	57
$Wjj$	550	152
$(tbq + tb) / (t\bar{t} + Wjj)$	0.14	0.21

Table 2. Numbers of events for  $3 \text{ fb}^{-1}$  (summed over  $t$  and  $\bar{t}$ ,  $e$  and  $\mu$  channels) for the two sets of cuts in Table 1.

(For a detailed comparison with the results of [1] see [8].) We are concerned that systematic errors in the understanding of the background will plague a direct counting experiment at a level that will make any claims of discovery suspect.

Under the assumption that a counting experiment is indeed insufficient, we turn to observables that (as in [4, 6]) make use of other aspects of the signal. For the dominant  $tbq$  production process the light quark, forward jet is a distinctive signature, which the backgrounds do not share. We make use of this feature in our analysis of both signal and background events by including in our event definition the properties of “the jet”, defined to be the highest- $p_T$  non-*b*-tagged jet. Since the  $tbq$  process arises from an initial state light quark or antiquark scattering off a gluon, the  $tbq$  system is typically boosted in the direction of the initial quark. Moreover the motion of the final state light quark is typically in the same direction as its parent quark (and the proton). (The reverse is true for  $\bar{t}$  production.) The structure of the electroweak interactions in both the production and decay of the top quark tends to align the momentum direction of “the jet” with that of the

final-state charged lepton. Thus the momentum vectors of the lepton and “the jet” are correlated as a result of both kinematics and spin polarization effects.

The  $t\bar{t}$  process shares none of these properties. At tree-level,  $t\bar{t}$  is separately C and P invariant, and shows none of the above asymmetries. The parity-invariance is violated at the next order [12], at a level both small and calculable. Moreover, there should be no strong correlation between the momenta of the lepton and the jets in the final state. Similar considerations apply, to a good approximation, to those QCD events which might pass our cuts, mainly events with fake leptons or with isolated leptons from heavy flavor decays. (See [8] for additional discussion of this point.)

The asymmetries and correlations in  $Wj^n$  are similar to those of  $tbq$  (unfortunately) although less pronounced. As with a  $t$  quark, a  $W^+$  is most likely to be produced moving in the proton direction. This leads to parity asymmetries which, though relatively small, are still quite large in absolute size compared to the signal. Correlations between the lepton and “the jet” are nonzero, though relatively small. Unfortunately, the size of the asymmetries and correlations in  $Wj^n$  appears to be very sensitive to assumptions, cuts, Monte Carlo parameters, and tagging, and will be a source of significant systematic error.

To make the use of these special properties of the signals and backgrounds we consider two-dimensional distributions in pseudo-rapidity. Since the  $p\bar{p}$  initial state of the Tevatron is a CP eigenstate, the differential cross-section  $d^2\sigma^+/d\eta_j d\eta_\ell$  describing the rapidity distributions of “the jet” and the charged lepton in events with a *positively* charged lepton, and the corresponding distribution  $d^2\sigma^-/d\eta_j d\eta_\ell$  for processes with a *negatively* charged lepton, *must* be CP invariant:

$$\frac{d^2\sigma^+}{d\eta_j d\eta_\ell}(\eta_j, \eta_\ell) = \frac{d^2\sigma^-}{d\eta_j d\eta_\ell}(-\eta_j, -\eta_\ell) .$$

Consequently, we can combine data from positively and negatively charged leptons by defining a *lepton-charge-weighted pseudo-rapidity*,  $\hat{\eta}_j = Q_\ell \eta_j$ ,  $\hat{\eta}_\ell = Q_\ell \eta_\ell$ , where  $Q_\ell$  is the lepton charge. The remainder of this discussion is based on the explicitly CP-invariant differential cross section

$$\frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(\hat{\eta}_j, \hat{\eta}_\ell) \equiv \frac{d^2\sigma^+}{d\eta_j d\eta_\ell}(\eta_j = \hat{\eta}_j, \eta_\ell = \hat{\eta}_\ell) + \frac{d^2\sigma^-}{d\eta_j d\eta_\ell}(\eta_j = -\hat{\eta}_j, \eta_\ell = -\hat{\eta}_\ell) .$$

To illustrate the characteristic properties of the various channels we will study[8] a simulated event sample defined by cuts somewhat more “relaxed” than those of Table 1, keeping a larger fraction of both the signal and the background. The simulated differences in shape are summarized in the

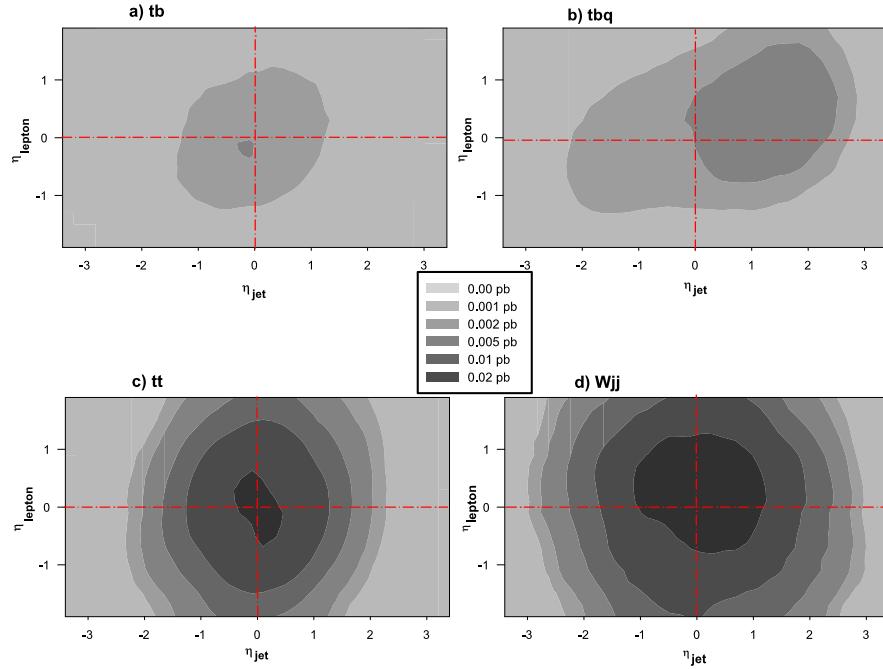


Fig. 2. Differential cross-section ( $d^2\sigma/d\hat{\eta}_j d\hat{\eta}_\ell$ , summed over  $t$  and  $\bar{t}$ ,  $e$  and  $\mu$ ) for the a)  $tb$  channel b)  $tbq$  channel, c)  $t\bar{t}$  channel, and d)  $Wjj$  channel.

contour plots of Fig. 2, which give the distributions ( $d^2\sigma/d\hat{\eta}_j d\hat{\eta}_\ell$ ) of the various processes in the  $(\hat{\eta}_j, \hat{\eta}_\ell)$  plane.

Figures 2a and 2c illustrate the relative symmetry of the  $tb$  and  $t\bar{t}$  channel, to be compared to the small asymmetry in the  $Wjj$  channel in Fig. 2d and the large asymmetry in the  $tbq$  signal channel of Fig. 2b. In particular, the  $tbq$  signal lies dominantly in the B quadrant, where the four quadrants of the  $(\hat{\eta}_j, \hat{\eta}_\ell)$  plane are labeled in the form  $\frac{A}{C} \mid \frac{B}{D}$ . Meanwhile  $tb$  is smaller with a less distinctive shape. By contrast,  $t\bar{t}$  is large though symmetrically distributed, and  $Wjj$  is large but has small asymmetries between the four quadrants, with slightly more cross-section in the A and B quadrants than in C and D.

To capture quantitatively these differences in shape between signal and background, we define three orthogonal functions in the  $(\hat{\eta}_j, \hat{\eta}_\ell)$  plane. Any

differential cross-section can be written as a sum of three components

$$\frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(\hat{\eta}_j, \hat{\eta}_\ell) = \bar{F}(\hat{\eta}_j, \hat{\eta}_\ell) + F_+(\hat{\eta}_j, \hat{\eta}_\ell) + F_-(\hat{\eta}_j, \hat{\eta}_\ell), \quad (1)$$

where the components are of the form

$$\begin{aligned} \bar{F}(\hat{\eta}_j, \hat{\eta}_\ell) &\equiv \frac{1}{4} \left[ \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(\hat{\eta}_j, \hat{\eta}_\ell) + \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(-\hat{\eta}_j, -\hat{\eta}_\ell) \right. \\ &\quad \left. + \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(\hat{\eta}_j, -\hat{\eta}_\ell) + \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(-\hat{\eta}_j, \hat{\eta}_\ell) \right], \end{aligned} \quad (2)$$

$$\begin{aligned} F_+(\hat{\eta}_j, \hat{\eta}_\ell) &\equiv \frac{1}{4} \left[ \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(\hat{\eta}_j, \hat{\eta}_\ell) + \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(-\hat{\eta}_j, -\hat{\eta}_\ell) \right. \\ &\quad \left. - \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(\hat{\eta}_j, -\hat{\eta}_\ell) - \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(-\hat{\eta}_j, \hat{\eta}_\ell) \right], \end{aligned} \quad (3)$$

$$F_-(\hat{\eta}_j, \hat{\eta}_\ell) \equiv \frac{1}{2} \left[ \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(\hat{\eta}_j, \hat{\eta}_\ell) - \frac{d^2\sigma}{d\hat{\eta}_j d\hat{\eta}_\ell}(-\hat{\eta}_j, -\hat{\eta}_\ell) \right]. \quad (4)$$

These functions are orthogonal in the sense that the integral of any (non-identical) pair over any symmetrically-defined region of the  $(\hat{\eta}_j, \hat{\eta}_\ell)$  plane vanishes. Most importantly, the functions provide important physical information about the symmetry properties of the differential cross-section.  $\bar{F}$  and  $F_+$  are parity-even while  $F_-$  is parity-odd; thus  $F_- = 0$  (within statistics) for any parity-even distribution. Meanwhile  $F_+$  will also vanish if the distribution is parity-even *and* the leptons and jets are uncorrelated. By construction  $\bar{F}$  and  $F_+$  have four-way symmetry under reflection in the  $(\hat{\eta}_j, \hat{\eta}_\ell)$  plane, while  $F_-$  has two-way symmetry (quadrants A and D are related, as are B and C, but quadrants A and B are independent).

The fact that the signal has strong asymmetries and correlations not present in the backgrounds yields the following expectations,

$$\begin{aligned} \bar{F}^{t\bar{t}} &\gg F_\pm^{t\bar{t}}; \quad \bar{F}^{Wj^n} > F_\pm^{Wj^n}; \quad \bar{F}^{tbq} \sim F_\pm^{tbq}, \\ \bar{F}^{t\bar{t}} &\sim \bar{F}^{Wj^n} \gg \bar{F}^{tbq}, \\ F_+^{t\bar{t}} &\sim F_+^{Wj^n} \sim F_+^{tbq}, \quad F_-^{t\bar{t}} \ll F_-^{Wj^n} \sim F_-^{tbq}. \end{aligned}$$

Thus the backgrounds are very large only in  $\bar{F}$ , while the signal has a much larger role to play in the other functions, especially away from the center of the  $(\hat{\eta}_j, \hat{\eta}_\ell)$  plane.

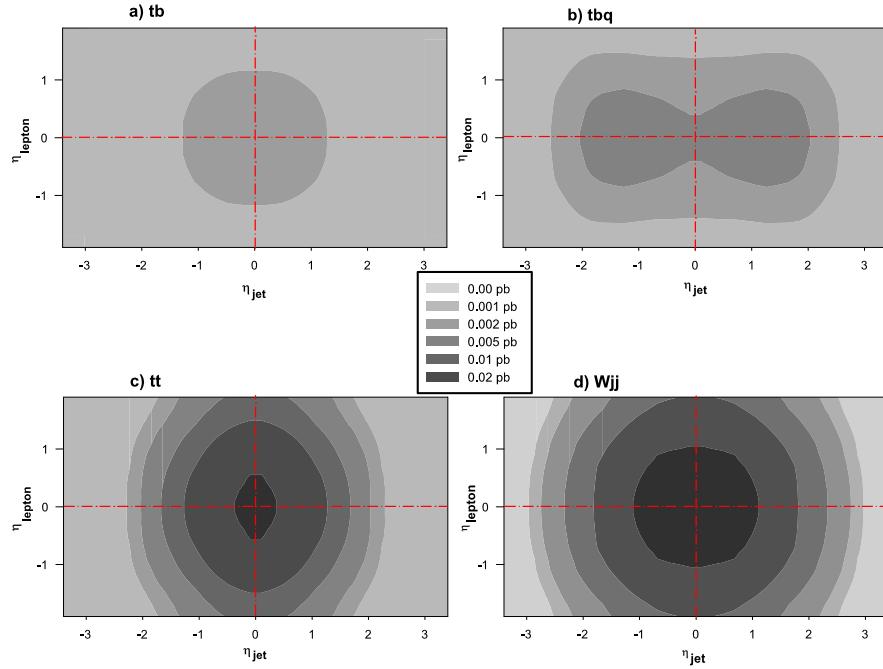


Fig. 3. Contour plots for the function  $\bar{F}(\hat{\eta}_j, \hat{\eta}_\ell)$  for a)  $tb$ , b)  $tbq$ , c)  $t\bar{t}$ , and d)  $Wjj$  channels (summed over  $t$  and  $\bar{t}$ ,  $e$  and  $\mu$ ).

These expectations are illustrated in Figs. 3, 4 and 5, where the functions  $\bar{F}, F_+, F_-$  are shown, for  $tb$ ,  $tbq$ ,  $t\bar{t}$ , and  $Wj^n$ . Note, in particular, the presence of the symmetry properties discussed above.

Thus we are led (see [8] for more details) to suggest the following general approach. First construct, for both the data and the Monte Carlo simulations, the  $\bar{F}, F_+$  and  $F_-$  functions. Using these functions, as well as information obtained from other measurements, we systematically test our understanding of each process. The  $\bar{F}$  function allows a measurement of the sum of the backgrounds without much contamination from signal. Assuming that the separation of  $Wj^n$  from  $t\bar{t}$  can be obtained using the fact that the  $t\bar{t}$  process can be measured and predicted with reasonable accuracy, we can then cross-check our understanding of the  $Wj^n$  background using part of the  $F_-$  distribution (located roughly in quadrant A) where the signal is negligible. Finally, one can attempt to measure the signal from  $F_+$  and from another part (located largely in quadrant B) of the  $F_-$  distribution.

A complete analysis of the above ideas has been carried out in [8], in-

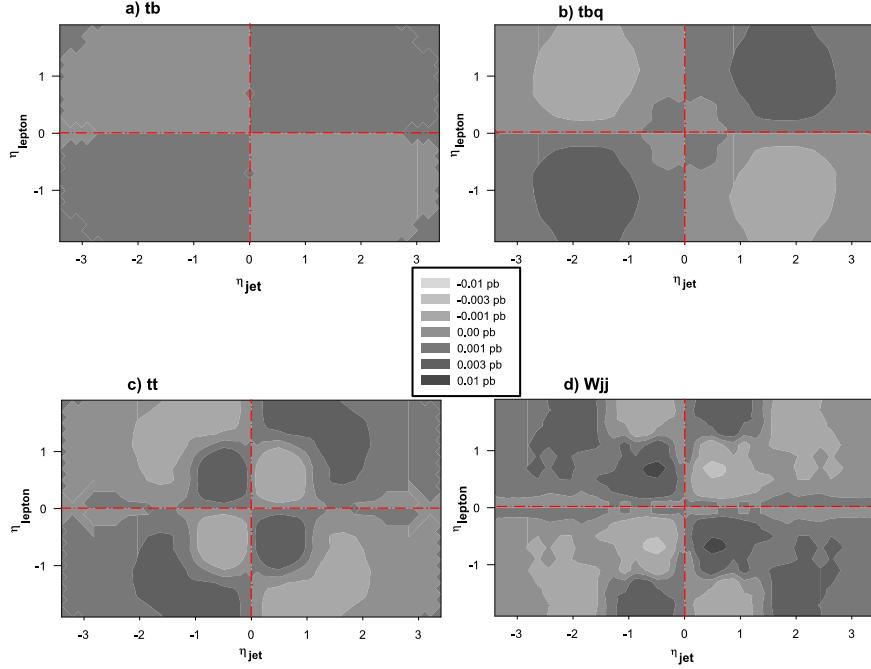


Fig. 4. Contour plots for the function  $F_+(\hat{\eta}_j, \hat{\eta}_\ell)$  for a)  $tb$ , b)  $tbq$ , c)  $t\bar{t}$ , and d)  $Wjj$  channels (summed over  $t$  and  $\bar{t}$ ,  $e$  and  $\mu$ ).

cluding estimates of the associated uncertainties, both statistical and systematic. The primary lesson is that, even when using the shape variables discussed above, the contributions of the backgrounds, especially  $Wj^n$ , cannot be rendered truly small compared to the signal. Thus it is essential that we understand the backgrounds with high precision, including their shapes as employed here. This last point is especially challenging for the  $Wj^n$  case, which receives comparable contributions from events with tags of  $b$  quark jets, tags of  $c$  quark jets and mistags of jets with no heavy flavor. Likewise there are comparable contributions from when the heavy-flavor quark is present in the short-distance scattering and when it is produced in the subsequent showering. This means that our ability to accurately simulate the background depends on our understanding of a multitude of different specific channels, each with their own shapes and their own dependence on cuts, parton distributions and other parameters.

In summary, a counting experiment for discovery of electroweak single-

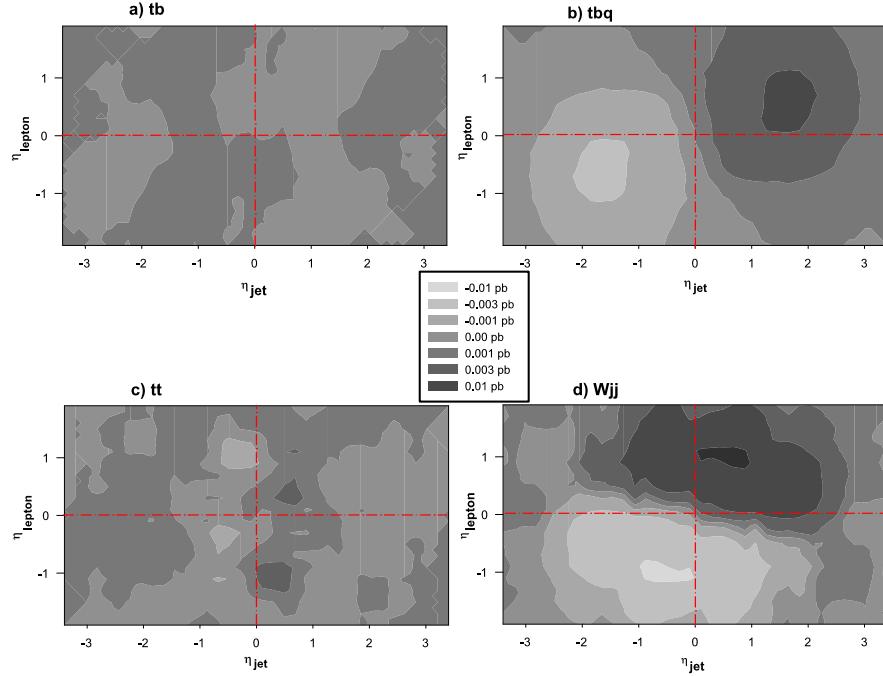


Fig. 5. Contour plots for the function  $F_- (\hat{\eta}_j, \hat{\eta}_\ell)$  for a)  $tb$ , b)  $tbq$ , c)  $t\bar{t}$ , and d)  $Wjj$  channels (summed over  $t$  and  $\bar{t}$ ,  $e$  and  $\mu$ ).

top production appears very challenging. We have explored the possibility of using the distinctive shape of this process to separate it from background. We have noted that the distributions for  $t\bar{t}$  and for QCD in the  $(\hat{\eta}_j, \hat{\eta}_\ell)$  plane are largely symmetric, while that of the signal is not; the  $Wj^n$  ( $W$ -plus-jets) background is intermediate between them. Constructing the functions  $\bar{F}, F_\pm$ , which have various symmetry properties, we find that the statistical and systematic errors in the functions  $F_\pm$ , which are orthogonal to the function  $\bar{F}$  (that would be used in a counting experiment), can be brought close to reasonable size without using extreme cuts. Our method largely removes  $t\bar{t}$  and QCD events from the observables, making extreme cuts on  $t\bar{t}$  unnecessary, and focusing attention on  $Wj^n$  as the main background. The most challenging problem is understanding the shape of the  $Wj^n$  background. We believe this calls for a dedicated study of the the rates, shapes, and flavor content (especially of bottom versus charm) of both  $Wj^n$  and  $Zj^n$ , with zero, one and two tagged jets, blended with theoretically precise predictions, and careful tuning and cross-checking of Monte Carlo simulations.

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